Studies of Soft-QCD at LHCb

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on behalf of the LHCb collaboration
Introduction

Recent QCD studies which are presented in this talk:

- Energy Flow measurement
- Prompt Hadron Ratios
- Prompt Charm production

LHCb has great potential for Soft-QCD measurements

- Excellent vertex resolution & coverage of backwards tracks
- Particle ID from Ring Imaging Cherenkov detectors
- Unique pseudorapidity coverage at the LHC (2 < \eta < 5)
**Energy Flow**

Energy Flow (EF): \[
\frac{1}{N_{\text{int}}} \frac{dE_{\text{total}}}{d\eta} = \frac{1}{\Delta \eta} \left( \frac{1}{N_{\text{int}}} \sum_{i=1}^{N_{\text{part,}\eta}} E_{i,\eta} \right)
\]

- Energy Flow at large pseudorapidity probes multi-parton-interactions (MPI) & parton radiation
- MPI describes the structure of the underlying event
- Valuable input for generator tunings

Comparison to *PYTHIA* and *cosmic-ray* event generators

Energy Flow measured in 4 different event classes:

- **Inclusive minimum-bias:** at least 1 track in \(1.9 < \eta < 4.9 \) and \( p > 2 \) GeV
- **Hard- scattering:** at least 1 track in \(1.9 < \eta < 4.9 \) and \( p_T > 3 \) GeV
- **Diffractive enriched:** no tracks in \(-3.5 < \eta < -1.5 \)
- **Non-diffractive enriched:** at least 1 track in \(-3.5 < \eta < -1.5 \) \{Large rapidity gap for diffractive processes\}
Energy Flow

Total EF = (charged + neutral) EF

- Energy Flow increases with larger momentum transfer:
  \( EF_{\text{hard}} > EF_{\text{non-diff}} > EF_{\text{incl}} > EF_{\text{diff}} \)

- Uncertainties dominated by systematics
- Uncertainties decrease towards larger \( \eta \)

**Compared to PYTHIA predictions**

- **PYTHIA 6 tunes:**
  - for all samples the EF is
  - \( -> \) overestimated at small \( \eta \)
  - \( -> \) underestimated at large \( \eta \)
- **PYTHIA 8 tunes:**
  - EF in all samples is well described at large \( \eta \), except for hard scattering
Compared to cosmic-ray generators (not tuned to LHC data!)

- EPOS & SYBILL
  - good description of minimum-bias and non-diffractive events

- QGSJET models
  - overestimated EF in minimum-bias and non-diffractive events, but good description of hard scattering

- Best description by SYBILL

- All models underestimate EF in the diffractive sample

input for PYTHIA & cosmic-ray generators!
Prompt Hadron Ratios

Analyzed data: 0.3nb⁻¹ at \( \sqrt{s} = 0.9 \)TeV and 1.8nb⁻¹ at \( \sqrt{s} = 7 \)TeV

Measured ratios as function of \( \eta \) and \( p_T \):

Same-particles \( \frac{K^-}{K^+}, \frac{\pi^-}{\pi^+}, \frac{\bar{p}}{p} \)

Different-particles \( \frac{p+\bar{p}}{\pi^++\pi^-}, \frac{K^++K^-}{\pi^++\pi^-}, \frac{p+\bar{p}}{K^++K^-} \)

- \( \frac{\bar{p}}{p} \) is an observable to test baryon number transport

- All ratios are probes for hadronisation models
  - import input of generator optimization

  - PID efficiencies from data using resonances: \( K^0_s \rightarrow \pi\pi, \phi \rightarrow KK \) and \( \Lambda \rightarrow p\pi \)
  - Dominant systematic uncertainty from PID due to limited calibration sample size
Same-particle ratios

\[ \frac{K^-}{K^+} \]

\[ \frac{\sqrt{s} = 0.9 \text{ TeV}}{\sqrt{s} = 7 \text{ TeV}} \]

\[ \frac{\sqrt{s} = 0.9 \text{ TeV}}{\sqrt{s} = 7 \text{ TeV}} \]

\[ \frac{\pi^-}{\pi^+} \]

Ratios close to unity

In general, \( \frac{K^-}{K^+} \) and \( \frac{\pi^-}{\pi^+} \) well described by tested PYTHIA generator tunes

Same-particle ratios

- For 0.9 TeV $\bar{p}/p$ shows significant $\eta$ dependence, model with extreme baryon number transport (NOCR) favored
- For 7 TeV Perugia0 and LHCb tune better than NOCR tune
- $\bar{p}/p$ as function of rapidity loss: consistent results, much better precision
- Fit to LHCb & ALICE data: *Regge model* of baryon transport

\[ \sqrt{s} = 0.9 \text{ TeV} \]
\[ \sqrt{s} = 7 \text{ TeV} \]

\[ \frac{\bar{p}}{p} \]

Rapidity loss $\Delta y = y_{beam} - y$
\[ y_{beam} = 8.9 \ (6.9) \text{ at } \sqrt{s} = 7 \ (0.9) \text{ TeV} \]
Different-particle ratios

\[ \frac{p + \bar{p}}{\pi^+ + \pi^-} \]

\[ \sqrt{s} = 0.9 \text{ TeV} \]

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ \frac{K^+ + K^-}{\pi^+ + \pi^-} \]

\[ \sqrt{s} = 0.9 \text{ TeV} \]

\[ \sqrt{s} = 7 \text{ TeV} \]

- Large discrepancies to Perugia0 and Perugia NOCR tunes
- LHCb tune is fine

- In general, no model is able to describe the whole measurements

• $\sqrt{s} = 7\text{TeV}$ data set, $\mathcal{L}=0.15nb^{-1}$

• Fiducial region: $2.0 < \eta < 4.5$; $0 < p_T < 8\text{ GeV}$

• Use fully reconstructed decays of prompt charm hadrons: $D^0, D^+, D^{*+}, D_s^+\text{ and } \Lambda_c^+$

• PID efficiencies from data using $K_S^0, \phi\text{ and } \Lambda$ decays

• Prompt signal yield gained from multidimensional extended maximum likelihood fit (mass + IP distribution)

Cross-section measurement tests QCD fragmentation and hadronisation models
Prompt Charm Production

Differential cross-sections compared to theoretical expectations, which reproduce Tevatron & ALICE measurements in central rapidity region

- Fixed order with next to leading-log resummation (FONLL) using CTEQ 6.6
- NLO calculation in the Generalized Mass Variable Flavour Number Scheme (GMVFNS) using CTEQ 6.5 and CTEQ 6.5c2 (intrinsic charm)

- Good agreement with our measurement
- Effect of intrinsic charm is predicted to be small in this phase space region
Prompt Charm Production

Good agreement in these modes as well

Total charm cross-section* ($p_T<8$GeV, $2.0<\eta<4.5$):

\[ \sigma(c\bar{c}) = 1419\pm12\text{(stat)}\pm116\text{(syst)}\pm65\text{(frag)} \mu b \]

* Combination of bins where rel. precision < 50%, otherwise using extrapolation based on Pythia tunes (Perugia0, PerugiaNOCR, Perugia2010 & LHCb tune)
LHCb allows Soft-QCD precision studies in unique kinematic range at the LHC

- measurements performed for $\sqrt{s} = 0.9$ and 7 TeV pp data:
  - Energy Flow measurements give input to generators tunings and MPI / underlying event models
  - Prompt hadron ratios test baryon number transport and hadronisation
  - Prompt charm production probes hadronisation and fragmentation models

- Measurements will be supplemented with pp data at $\sqrt{s} = 2.76$ and 8 TeV

- Large data set of Proton-Ion (pPb / Pbp) data at $\sqrt{s_{NN}} = 5$ TeV is currently analyzed
  - particle production, particle ratios, charge ratios, meson production, particle correlations etc...

Stay tuned for new results!
Charged Energy Flow
Energy Flow

Charged Energy Flow

![Graphs showing charged energy flow data and simulations for different event types.](image)

- Inclusive minbias events
- Hard scattering events
- Diffractive enriched events
- Non-diffractive enriched events

**Data**
- EPOS 1.99
- QGSJET01
- QGSJETII-03
- SIBYLL 2.1

**MC/Data**
- Systematic Uncertainty
Different-particle ratios

\[ \frac{(p + \bar{p})}{(K^+ + K^-)} \]

\( \sqrt{s} = 0.9 \text{ TeV} \)

\( \sqrt{s} = 7 \text{ TeV} \)
Prompt charm production in $pp$ collisions at $\sqrt{s} = 7$TeV

$D^0 \rightarrow K^- \pi^+$

$D^{*+} \rightarrow D^0(K^- \pi^+)\pi^+$

$\Lambda_c^+ \rightarrow p K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D_s^+ \rightarrow \phi(K^- K^+)\pi^+$
Prompt charm production in $pp$ collisions at $\sqrt{s} = 7\text{ TeV}$

$D^0 \rightarrow K^- \pi^+$

$D^{*+} \rightarrow D^0 (K^- \pi^+) \pi^+$

$\Lambda_c^+ \rightarrow p K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D_s^+ \rightarrow \phi (K^- K^+) \pi^+$
PYTHIA tunes

Non default PyTHIA parameters in the LHCb simulation software

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Perugia0 corresponding PyTHIA parameters

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PARP(82): UE IR cutoff at reference ecm, Pythia 0: 3.4  Pythia NOCR: 3.19
PARP(89): Reference ecm
PARP(90): UE IR cutoff ecm scaling power